Sure bet or scientometric mirage? : an assessment of Chinese progress in nanotechnology

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Abstract:

After launching its national strategy to promote nanotechnology development in 2001, China has devoted an increasing amount of R&D investment from government and industry to the field, produced a soaring number of scientific publications, established several new specialized institutions, and expanded its postgraduate programs in related subjects. The hope that China can pass through a window of opportunity to catch up and become a leading nation in nanotechnology has never been higher. However, an evaluation of the Chinese performance according to targets set in the national strategy suggests that China has lagged behind most advanced countries in terms of the impact (citations) of its scientific research. China has not yet performed satisfactorily in the areas of commercialization and application of the technology either, due to the limited technological capabilities of indigenous companies and a lack of incentives for them to actively engage in commercialization and industrial development.

Keywords:

Nanotechnology; China; R&D; Technological Catching-up

JEL codes: O14, O33, O38

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1. Introduction

China's global rise in research and development (R&D) in nanoscience and nanotechnology (hereafter referred to as "nanotechnology") has been phenomenal in the past decade. In 1998, there were merely 1,875 scientific publications out of China, compared with 9,468 in the US and 4,423 in Japan.[1] In 2007 Chinese nanotechnology publications outnumbered those from Japan by a wide margin and occupied second place in the world in terms of number of publications, trailing only the US. China's share in the world's nanotechnology publications was only 6 percent in 1998. By 2007, however, China accounted for 19 percent. Figure 1 lists the number of nanotechnology publications produced by the world's 10 most prolific countries over the 1998–2007 period. A calculation of the average annual growth rate in the number of articles by the 10 most prolific countries reveals rapid growth in China, South Korea, and India. China's average annual growth rate of 27 percent each year between 1998 and 2007 is nothing short of extraordinary. In contrast, the other countries in the top 10, including the US, Japan, Germany, France, the UK, Italy, and Russia achieved only 6 to 10 percent rates in annual growth.

(Insert Figure 1 here)

China's progress is less impressive in patenting than in publishing. Counting the patent applications with the European Patent Office's nanotechnology classification Y01N in the PATSTAT database,[2] we find that Chinese patents accounted for only 0.88 percent of the world's total, in comparison with the US share of 34.2 percent and the Japanese share of 19.7 percent. Although China's share is very small, the number of the patents filed by Chinese applicants grew rapidly, at an average rate of 36.8 percent per year, from 1998 through 2007 (Figure 2). Excepting South Korea, where the rate grew by an extraordinary 77.7 percent

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[1] The analysis of scientific publications in this article is based on the MERIT Database of Worldwide Nanotechnology Scientific Publications. It is composed by scientific publications indexed by the Web of Science. The search strategy used to define nanotechnology publications is developed by the Georgia Institute of Technology and described in Porter et al. [1]. Huang et al. [2] compared this search strategy and other popular strategies.

[2] Throughout this paper, a nanotechnology patent is defined as a patent with a Y01N classification. The classification code Y01N is attached to a patent application when the patent examiner at the European Patent Office considers it to be related to nanotechnology. A detailed introduction of the Y01N classification is provided by Scheu et al [5].

annually, the applications in the rest of the top 10 countries increased more slowly than in China. Some leading countries, such as Japan and France, have seen negative rates of growth in nanotechnology patents.

(Insert Figure 2 here)

According to Lux Research [3], the US and Japanese governments invested US$1816 million and US$1060 million (by purchasing power parity or PPP), respectively, on nanotechnology R&D in the 2005–2007 period. The Chinese government invested US$PPP893 million in the same period, which positions China in third place in the worldwide ranking (Figure 3). However, corporate funding in China amounted to only US$PPP348 million, which was only slightly more than one-third of government funding. Ranked by corporate funding, China was ranked fifth in the world after the US (US$PPP2,362 million), Japan (US$PPP2,038 million), Germany (US$PPP467 million) and South Korea (US$PPP384 million). A different estimation by the European Commission [4] showed that the Chinese government invested 83 million euros in 2004 on nanotechnology R&D, in comparison with the US government's 1.2 billion euros and the Japanese government's 750 million euros. China was thus ranked after the US, Japan, Germany, France, South Korea, and the UK by amount of public investment in nanotechnology R&D in 2004. Indicators of scientific publications, patent applications and public and corporate funding all reveal that China has been closing the gap with the leading countries in this emerging technology field in the past decade and is becoming a major player in the world.

(Insert Figure 3 here)

Interestingly, China began to make strides in the field of nanotechnology rather early, almost at the same time that other advanced countries decided to boost their investments. As evidence of this, China's National Nanotechnology Development Strategy (2001–2010) was announced in the same year as the National Nanotechnology Initiative in the US. However, China's enthusiastic embrace of nanotechnology in the early 2000s was neither rooted in a solid forecast projecting when the technology would mature and be commercialized nor backed by confidence that indigenous Chinese industries would have the capacity to reap the fruits of scientific development in the country. In a country whose GDP per capita was merely US$949 in 2000 (at 2000 prices), there were surely many acute challenges that the government had to meet. In this sense, large-scale government investment in China seems difficult to be justified. Questions thus emerge in a retrospective review of Chinese policy and funding programs that support nanotechnology development. What motivates Chinese science and technology policy makers to resolutely concentrate the country's limited resources on this emerging field? How do we assess progress in nanotechnology R&D in China? These questions have been circulated in the international S&T community, but they are rarely addressed in scholarly work.

In this paper, we aim to fill the gap in the literature by assessing the development of nanotechnology in China through the perspective of technological catching-up and economic development. We study Chinese organizations that are engaged in nanotechnology R&D, S&T programs that support this field, and the key policies that have contributed and continue to contribute to technology development. By drawing insights from the theory of technological catching-up and economic development, we discuss the so-called Chinese model of promoting nanotechnology development and its implications for other developing countries. The remainder of the chapter is organized as follows: Section 2 reviews the literature on technological leapfrogging and catching-up and discusses the motivation behind the Chinese government's investment in developing nanotechnology. Section 3 reviews the key policies enacted by the Chinese government and identifies the targets set in policy documents in order to evaluate China's progress. Section 4 evaluates China's achievement in nanotechnology development across four areas—funding, competence building, scientific research, and commercialization and application of nanotechnology. Section 5 discusses the so-called Chinese model of nanotechnology development and adds concluding remarks.

2. The theory of technological catching-up and reflection on nanotechnology development in China

Technological catching-up in East Asian countries or regions, including South Korea, Taiwan, China, and Singapore, has been studied intensively by scholars. Research on the information and communication technologies industry [6, 7], the semiconductor industry [8], the electronics industry [9], the digital TV industry [10], the computer numerically controlled machine tool industry [11, 12], and the telecommunication industry [13, 14] has documented successful cases of catching-up in the region. These scholarly studies often discuss the role of government in creating conditions that are conducive to successful catching-up. If a window of opportunity for firms and industries can be identified by studying the conditions that are necessary for catching-up, it should be possible for a government to replicate successful cases and enact policies that enhance the technology capabilities of firms or industries, improve the business environment in which they operate, and ultimately increase the probability of successfully catching-up. We discuss China's progress in nanotechnology in this section by focusing on two issues: conditions conducive to catching up and government policies.

2.1 Window of opportunity and conditions conducive to technological catching-up

Perez and Soete [15] argued that there are four entry barriers that latecomers must overcome in order to successfully catch up, which include minimal fixed investment, scientific and technological knowledge, relevant skills and experience, and location advantages. Fixed investment denotes the necessary investment in equipment, machinery, and production lines. Latecomers usually incur the cost of producing or assimilating the necessary scientific and technological knowledge for innovation, because they have to invest in time and personnel for experiments, undergo trial-and-error learning, install equipment and instrumentation, and incur prototype expenses. Latecomers' skills and experience are required throughout the entire business process, from purchasing to production to marketing to distribution to sales. The location advantages are positive externalities inherent to the environment in which latecomers plan to operate. Such advantages might involve distance from equipment suppliers, soundness of the transport infrastructure, local availability of competent design, and construction and engineering contractors, all of which can make the cost of production significantly different from one location to another.

Perez and Soete [15] contended that, in the new product introduction phase, latecomers are not at a great disadvantage because the entry barriers they face in terms of fixed investment and relevant skills and experience should be low. After all, in a new industry even the leaders are still in the process of generating investment and acquiring the necessary skills and experience. However, the requirement involving science and technological knowledge would likely be difficult to meet, as original design and engineering demands sound knowledge. The barrier involving advantages in location is also likely to be high, as the relationship between producers and the environment in which they operate needs to be enhanced to generate positive externalities. Perez and Soete concluded that the window of opportunity available to developing countries for catching-up lies in the new product introduction phase, especially if such countries can accumulate science and technological knowledge and location advantages relatively quickly.

Perez and Soete's theoretical proposition was supported by a real case, namely South Korea's catching-up in CDMA technology [16]. CDMA technology was an emerging technology when the South Korean government and several South Korean firms considered developing the country's cellular phone system. Competing technologies include the analogue system in the US and the GSM system in Europe. Because of technological and market uncertainty, some Korean service providers and system manufacturers had strong reservations about the plan for developing the world's first CDMA system. However, Samsung, LG, the Ministry of Information and Telecommunication and the Electronics and Telecommunication Research Institute finally chose the technology because they thought that it would take much less time to catch up with the frontrunners in establishing a system based on an emerging technology. South Korean firms managed to obtain access to the core technology through the US-based firm Qualcomm and diversified the risk of R&D through a public-private consortium. They were ultimately able to develop core technologies (chips) for the CDMA system and became world leaders.

Supporting Perez and Soete's view and echoing Lee and Lim's finding, Niosi and Reid [17] argued that large developing countries with strong public sectors that are able and willing to maintain a long-term effort to overcome entry barriers should be able to catch up with advanced countries in biotechnology and nanotechnology. The Chinese government's large investment in nanotechnology R&D and the corresponding rapid growth in nanotechnology publications and patents demonstrated in the previous section suggest that China is overcoming barriers involving science and technological knowledge. Given that nanotechnology remains in the initial stage of commercialization as this article is written, requirements in terms of fixed investment, skills and experience, and location advantages should not be insurmountably high. We argue that China actually stands in a very favorable position from which to pass through the window of opportunity.

It may take quite a long time for public investment in China to pay off given the uncertainty of nanotechnology. Without funding, however, obsolescence is virtually guaranteed. As the US, Europe, Japan, and many other national and regional governments launched nanotechnology development strategies in the late 1990s and the beginning of the 2000s, it was only logical for China to jump on the bandwagon. With considerable scientific and technological knowledge already built up, it is possible for China to generate technological breakthroughs on the one hand, while on the other hand monitoring and absorbing technological development elsewhere in the world on the basis of which to generate its indigenous technological capability. In this sense, China's large public investment in nanotechnology R&D is more of a sure bet because an earlier and firmer commitment to the technology means a higher probability that indigenous industry will compete effectively when the technology matures. The question remains, however, whether the government can institute a policy framework that is conducive to home-grown innovation and the emergence of indigenous companies.

2.2 Government policy for promoting technological catching-up

Governments play an indispensable role in technological catching-up in East Asian countries and regions. They share the risk with private firms in R&D of new technologies, facilitate indigenous firms as they absorb and assimilate advanced foreign technology, and create an environment favorable for growth and competitiveness on the part of indigenous firms. Government policy instruments include promoting education, training, and research through establishing government-funded research institutes; forming public and private R&D consortia; supporting market protection, government procurement, and export subsidies; and bargaining with multinational enterprises over technological transfer and domestic content requirements. In the following discussion, these policies are described in detail with reference to examples provided in the literature.

Economic catching-up is historically associated with a policy of promoting the development of academic institutions. Academic training in chemistry in German and American universities contributed greatly to the catching-up and forging ahead of the chemical industry in the two countries in the period spanning the second half of the nineteenth century and the early twentieth century [18]. Japanese universities also played an important role in the period during which the economy was catching up with its Western counterparts after the Meiji restoration. The Japanese government was keen on recruiting foreign scientists and engineers from Western Europe and the US to assist local firms in adopting foreign technologies and also to take up teaching and research positions in its universities.

Similar stories played out in South Korea, Taiwan, and Singapore. According to Lee [19], the South Korean government established a series of government-funded research institutes in the 1960s and 1970s. The government did not demand an immediate return from these public research institutes, instead granting them full autonomy in allocating their operational funds. In addition to conducting contract research for industry and training R&D personnel, governmental research institutions attracted overseas scientists, many of whom played key roles in developing heavy and high-tech industries from the 1970s onward. Moreover, the existence of public institutions heightens the social status of scientists and engineers, attracting the best Korean students to study science and engineering.

The governments in South Korea and Taiwan also actively promoted public and private R&D consortia, which proved to be instrumental in absorbing and assimilating foreign technologies. When South Korea developed its CDMA and D-RAM technologies, the R&D consortium forged by the government reduced technological uncertainty by offering up-to-date information on technology trends and identifying appropriate targets for R&D projects [16]. In the high definition TV industry in South Korea, half of the budget for the public and private consortium was paid by the government and half was paid by the private sector. The consortium encouraged private firms to engage in risky R&D activities by channeling funding and forming a network of researchers from industry-related, university-related, and governmental research institutes [10]. Similarly, in the Taiwanese computer numerically controlled machine tool industry, a government-funded research institute, Mechanical Industry Research Laboratories, assisted private firms in designing machine tools and machining centers and subsidized their R&D costs. It was estimated that private firms paid only about one-third of the manpower costs involved in running the governmental laboratories. In addition, signing a contract with the laboratories usually guaranteed a firm’s access to subsidized bank loans [12].

Measures providing market protection, export subsidies, and government procurement practices favorable to domestic firms were not uncommon in East Asian countries. In the Taiwanese machine tool industry, a licensing system was used to prevent the import of machinery when equivalent products in terms of price and quality were available locally [12]. In the South Korean computer numerically controlled machine tool industry, only domestic companies were allowed to supply products below a certain size limit. The size limit was set very large, so most foreign lathes could not be imported. The government also set up a buyers’ credit system that was composed by the Procurement Fund for Locally-Produced Machinery for domestic users and Long-term Credit Financing for foreign buyers [11]. It is worthwhile mentioning that the international political and economic environment in the period of 1960–1980, when South Korea and Taiwan actively used industrial and trade policies to protect domestic markets and promote technological learning, no longer exists. It would be extremely difficult to adopt similar practices nowadays because of World Trade Organization (WTO) rules [6]. In addition, a strategy privileging market protection, government procurement practices that are favorable to domestic firms, and export subsidies is socially sub-optimal. For instance, when the importation of computer numerically controlled lathes was restricted in South Korea, local users were left with fewer choices and had to purchases less reliable machines from domestic producers [11, 16].

Governments in East Asian countries often bargained with multinational enterprises over technological transfer and imposed domestic content requirements on foreign direct investment. In the early 1980s, a foreign telecommunications company had to meet the following three conditions to set up a joint venture in China: 1) The Chinese side must hold a majority share of more than 50 percent; 2) the foreign side must transfer important technology to the Chinese side; 3) the customized large-scale integrated chips used in telecommunication equipment must be produced in cooperation with China. The Bell Telephone Manufacturing Company agreed to these conditions and established a joint venture, Shanghai Bell. It trained the first batch of

Chinese engineers in operating and manufacturing digital automatic switching systems. Without this company, there would have been no indigenous digital automatic switching systems and the eventual launch of the Chinese telecommunications industry would not have occurred [14].

Like its counterparts in other East Asian countries that financed R&D to promote technological catching-up, the Chinese government acted as the largest source of R&D funding for nanotechnology development in the country. Because of technological and market uncertainty, corporate investment alone would not have been up to the socially optimal level. It was thus left to the government to fill the gap. Public investment was turned into advanced infrastructure, equipment, instruments, and up-to-date technological standards, all of which can be considered public goods. The funded research projects and positions also attracted scientists and engineers, including young researchers, to the field and retained them. All of these conditions established the foundation for future industrial development.

Furthermore, Chinese policy makers at the central and local government levels set up several new institutions specializing in nanotechnology in the early 2000s. They included the National Center for Nanoscience and Technology in Beijing, the National Engineering Research Center for Nanotechnology in Shanghai, the China National Academy of Nanotechnology and Engineering and Nanotechnology Industrialization Base of China in Tianjin, the Suzhou Institute of Nano-tech and Nano-bionics (The Chinese Academy of Sciences), and so on. Among these institutions, the National Engineering Research Center for Nanotechnology in Shanghai is a limited corporation and also an industry-academy consortium, aiming to promote commercialization of nanotechnology.

In all, Chinese policies promoting nanotechnology development resemble those employed in promoting technological catching-up in other East Asian countries. Although China’s current policy focuses mainly on promoting education and research and industry-academy collaboration, as the technology matures additional policy instruments, such as enhanced government procurement practices, export subsidies, and technology transfer channels, are expected to be adopted as well.

3. Strategies for promoting nanotechnology development in China

As Bai [20, 21] documented, when nanotechnology R&D techniques were introduced to China in the 1980s, they were well received by Chinese scientists. The Chinese Academy of Sciences, the National Natural Science Foundation and the State Science and Technology Commission (the predecessor of the Chinese Ministry of Science and Technology) started to fund related research. In the 1990s, China hosted the 7th International Conference on Scanning Tunneling Microscopy (1993) and the 4th International Conference on Nanometer-Scale Science and Technology (1996), showcasing Chinese scientists' early participation in the field. From 1990 to 2002, nearly 1,000 projects were funded by the Ministry of Science and Technology (or the State Science and Technology Commission). Over the same period, the National Natural Science Foundation of China approved another 1,000 small-scale grants for projects related to nanotechnology. In short, the initiation of nanotechnology R&D in China can be dated back to the 1980s and 1990s. Intensive R&D activities did not begin, however, until the early 2000s.

In November 2000, the National Steering Committee for Nanoscience and Nanotechnology was established to oversee national policies and coordinate action. The minister of Science and Technology was the director of the committee. Vice directors of the committee included vice ministers of Science and Technology, the vice president of the Chinese Academy of Sciences, and the vice president of the National Natural Science Foundation. Officials from the Ministry of Education, the National Development and Reform Commission (a ministerial agency), and the Commission on Science, Technology and Industry for National Defense were also involved as members of the committee. The National Steering Committee for Nanoscience and Nanotechnology involved all the stakeholders and R&D funding organizations in the country, making concerted policy action at the national level possible. The committee drafted the first Chinese national policy document intended to promote nanotechnology development, which was announced as the National Nanotechnology Development Strategy (2001–2010) and was reminiscent of similar strategies or initiatives announced in other countries, such as the National Nanotechnology Initiative in the US.

The National Nanotechnology Development Strategy (2001–2010)—hereafter “the Strategy”—was composed by four parts. The first part, which introduced “opportunities and challenges,” highlighted the challenges that China was facing in the coming era of nanotechnology. The second part, which covered “principles,” proposed a set of tenets that nanotechnology development in China should follow. The third section of the Strategy focused on the following five “targets” that nanotechnology R&D in China should achieve within ten years. The last part of the Strategy outlined concrete policy measures and suggestions:

1) Strengthen basic research, construct a nanotechnology-related database, and develop national standards
2) Develop a set of key technologies
3) Commercialize and apply nanotechnology and upgrade traditional industries through the technology
4) Establish a few key national laboratories and research centers in the field with substantial government investment
5) Foster human resource development and train high caliber research personnel

The Strategy was the first comprehensive action plan designed to promote nanotechnology development in China. It emphasized the importance of basic science and called for strengthened financial support from the government. It prioritized commercializing nanotechnology and appropriating intellectual properties from R&D activities. The Strategy argues that competent R&D personnel is a key to the success of nanotechnology development and highlights the need for training and retaining scientists in the field, which evinces a long-term view of policy making. The Strategy mapped out a blueprint for Chinese nanotechnology development in the following decade. Many principles and thoughts expressed in the document have had a far-reaching impact on Chinese progress in the field. In the next section of this paper, the five targets set for nanotechnology R&D in China that were supposed to be met by 2010 are analyzed in detail and China’s performance regarding each aspect is evaluated (except for the second one, because it is extremely difficult to evaluate whether China has successfully developed some particular technologies).

Another important policy document that is comparable to the Strategy is the National Mid- and Long-Term Science and Technology Development Plan for 2006–2020 (hereafter the "Plan"), launched in March 2006. The Plan was not a policy document specific to nanotechnology, but rather a comprehensive document supporting Chinese science and technology development more broadly over the following 15 years. The Plan, which sets a number of priorities, represents the ambitious goal of sustaining economic growth and social development through home-grown innovation and increased government-led R&D investments. In the Plan, nanotechnology was highlighted primarily within the section on basic science research. It was considered one of the four major scientific research areas (or 'mega' projects) to receive substantial governmental funding. It was stated in the Plan that "nanotechnology is adopted by many countries as a strategic means of enhancing competitiveness and is one of the fields in which China can leapfrog technologically."

4 Evaluation of China's Achievements in Nanotechnology Development

The National Nanotechnology Development Strategy set five targets for nanotechnology development in China, to be met by 2010. In line with these targets, China's achievements are evaluated with reference to the following four aspects: funding, competence building, scientific research, and commercialization and application of the technology.

4.1 Funding

Since the 1980s China has established a series of funding programs that have set various priorities for supporting R&D activities in the country. Among these funding programs, the "973 program," which supports basic science research, the "863 program," which finances R&D in high-technology, particularly in the high-tech industry, and the "National Key Technology R&D program," which funds technology development, are the three main funding programs led by the Chinese Ministry of Science and Technology. The National Natural Science Foundation (hereafter "the Foundation"), which is independent of the Ministry of Science and Technology, is another important funding agency for basic science research. These programs, together with the funding managed by the Commission on Science, Technology and Industry for National Defense, are the main funding sources for nanotechnology R&D in China.

It has been estimated by Chunli Bai, vice president of the Chinese Academy of Sciences, that Chinese funding of nanotechnology development was equal to about US$160 million from 2001 to 2004. Such funding doubled each year between 1999 and 2002 [22]. The 973 program began to intensively fund nanotechnology research after the late 1990s. In June 2008, the Ministry of Science and Technology published the 2008–2010 budgets for all of the 897 projects funded by the 973 program during fiscal year 2006-2007. A rough estimation by the authors identified 84 projects (around 10 percent of the total projects) whose titles contained the word “nanometer.” These 84 projects will receive funding in the amount of RMB303 million (US$44 million) during the 2008–2010 period, accounting for 15 percent of the total funding from the 973 program over that period.

The 863 program supported R&D in nanotechnology under a “nano-material” rubric. Funding for the period of 2000–2005 was estimated to have reached RMB200 million (US$29 million) [23]. According to Huang et al. [24], the budget for the 863 program was five times greater than that of the 973 program in 2004. A rough estimation would suggest that funding under the 863 program in nanotechnology would be several times greater than that under the 973 program.

The Foundation began funding research in nano-materials after the 1980s. The total budget of the Foundation in 2008 amounted to RMB6.3 billion (US$920 million). It was estimated that, between 1991 and 2000, Foundation funding to support nanotechnology R&D reached RMB920 million (US$134 million) [23]. Such financial support was intensified between 2001 and 2003. In total, some 800 projects were funded by the Foundation between 2001 and 2003, with total budgets amounting to RMB196 million (US$29 million). In 2002, the Foundation included “nanotechnology basic science research” as one of several major research plans (mega projects).

Since the late 1990s, China’s Gross Expenditure on R&D (GERD) has been rapidly catching up with its Western counterparts (Figure 4). China’s GERD was about 36 percent, 55 percent, and 67 percent of those of Germany, France, and the UK in 1998, respectively. However, by 2006, China far surpassed those three countries and significantly closed the gap with Japan, the EU, and the US. Such rapid growth in overall R&D investment assures that nanotechnology R&D in China will receive increasing amounts of funding from public and private sources every year. As China has already become one of the major players in the field in terms of public and private R&D investment (Figure 3), it has fulfilled the first objective set in the Strategy with regard to increasing R&D funding to strengthen basic research and develop human resources.

(Insert Figure 4 here)

4.2 Competence building

Universities that are administrated by the Ministry of Education and research institutions that are affiliated with the Chinese Academy of Sciences are the major undertakers of basic nanotechnology research in China. It was estimated by Bai [21] that more than 50 Chinese universities and 20 research institutions in the Chinese Academy of Sciences across the country were engaged in basic nanotechnology research in 2005. Table 1 lists the 30 most prolific departments and institutions in China. Nine of the 30 departments and institutions are located in Beijing, which has made that city the most important center for nanotechnology research in the country. From 1998 to 2007, 261 departments or institutes in Chinese universities or the Chinese Academy Sciences produced more than 50 nanotechnology articles. Mapping these departments and institutes demonstrates that 22 percent are located in Beijing, 14 percent in Shanghai and 10 percent in Hong Kong (Table 2 and Figure 5). Beijing, Shanghai, and Hong Kong alone produced almost half of the Chinese scientific publications in nanotechnology. They are indeed the strongholds of basic nanotechnology research in the country.

(Insert Table 1 here)
(Insert Table 2 here)
(Insert Figure 5 here)

The Chinese nanotechnology R&D system with more than 50 universities and 20 institutions under the Chinese Academy of Sciences, with a total of 3,000 researchers involved by the end of

2005, was definitely respectable in size. However, the research activities carried out in these organizations were scattered across the country and suffered to a certain degree from a lack of synergy. The competition among these organizations for research funding made coordinated action, for example co-purchasing large and expensive scientific instruments, rather difficult. In addition, successful commercialization of nanotechnology depends on strong linkages between industry and the academy. Existing universities and institutions that emphasized basic science research did not, however, regard commercialization as their primary mission. To tackle these challenges, policy makers at the central and local government levels set up several new institutions specializing in nanotechnology at the beginning of the 2000s. The National Center for Nanoscience and Technology in Beijing and the National Engineering Research Center for Nanotechnology in Shanghai are two examples.

The National Center for Nanoscience and Technology (hereafter “the Center”) was co-established by the Chinese Academy of Sciences and Ministry of Education in March 2003. The founding organizations of the Center were the Chinese Academy of Sciences, Peking University, and Tsinghua University, all of which are predominant players in nanoscience research in China, as seen in Table 1. The initial funding for the center was RMB250 million (US$37 million), including RMB180 million from the National Development and Reform Commission (a ministerial agency), RMB50 million from the Ministry of Education and RMB20 million from the Chinese Academy of Sciences [25].

The Center aimed to gather the scattered resources from various research institutions affiliated with the Chinese Academy of Sciences, Peking University, and Tsinghua University and to strengthen cooperation among them. A vice president of the Chinese Academy of Sciences was appointed as the first director of the Center, and the vice presidents of Peking University and Tsinghua University were two of the four vice directors. The laboratories in the three institutions received subsidies from the Center and were included in a network of laboratories set up by the Center. Half of the subsidy received by the collaborative laboratories must be used to support experiments done by researchers from other organizations, which assures the openness of the network.

As one of its most important functions, the Center coordinated the development of Chinese nanotechnology standards. It hosts the secretariat of the National Committee of Standards on Nanotechnology, which approves Chinese standards for nanotechnology. Assisted by the Center, the National Committee of Standards on Nanotechnology had developed 15 standards by 2007. The Center also submitted standards proposals to the International Origination of Standardization. In March 2009, the testing laboratory in the Center was accredited by the China National Accreditation Service for Conformity Assessment, as a result of which the testing and calibration reports issued by the Center are recognized not only within China but also in other countries that have signed mutual recognition arrangements with China.

The National Engineering Research Center for Nanotechnology (hereafter “the Engineering Center”) was established based on a limited corporation in Shanghai in October 2003. It is funded by an industry-academy consortium. The consortium consists of Shanghai Jiaotong University, Fudan University, East China Normal University, the Shanghai Institute of Microsystem and Information Technology, the Shanghai Institute of Ceramics (the Chinese Academy of Sciences), the Zizhu Science-based Industrial Park, the Shanghai Science & Technology Investment Co. Ltd., the Bao Steel Group. Of the RMB182 million (US$27 million) in initial funding for the Engineering Center, RMB42 million came from the consortium and RMB60 million and RMB80 million came from the Shanghai municipal government and the central government, respectively [26].

In 2007, a project involved in the development of Ni-H batteries, carried out under the auspices of the Engineering Center, was successfully commercialized. The Engineering Center co-funded the Shanghai Wanhong Power and Energy Sources Co., Ltd., with the Shanghai Wanhong Industrial (Group) Investment Co., Ltd, the Shanghai Institute of Microsystem and Information Technology (a board member and founding organization of the Engineering Center), and the Shanghai Huge Development Co., Ltd., to commercialize the technology. The newly established company employed 150 staff members by 2009 and produced Ni-H batteries used in electric cars and bicycles and other industry sectors.

In short, these two newly founded institutions in China were diverse in their missions and activities. The National Center for Nanoscience and Technology in Beijing promoted cooperation, facilitated the sharing of facilities and equipment, and avoided duplicate investments between universities and institutions. It coordinated the development of nanotechnology standards in China, which provides a reference point on the basis of which governmental agencies can regulate products and markets related to nanotechnology. The National Center was also involved in the development of international nanotechnology standards, defending China's interests and participating in rule-setting for future industrial applications. It served as a contact point for international academic collaboration and actively promoted exchanges with scientific communities outside China. Alternatively, the National Engineering Research Center for Nanotechnology in Shanghai strongly emphasized industry-academy cooperation in commercializing nanotechnology. Representatives from several Shanghai-based venture capital companies and the Science Park sat on the board of the Engineering Center. The functions of these newly founded institutions matched up well with the fourth target set by the Strategy, according to which China should establish several key national laboratories and research centers in the field.

Another important aspect of competence building is training and retaining scientists and engineers in the field. We find no specific data regarding the number of scientists and researchers engaged in nanotechnology research in China. The best data we can obtain are those that indicate the total number of researchers and the number of students enrolled in and graduating from postgraduate programs in science and engineering in the country. As nanotechnology spans a variety of disciplines, including chemistry, physics, biotechnology, and material sciences, the available data on total researchers and science and engineering postgraduate programs arguably demonstrate Chinese progress in the field. The total number of Chinese researchers was already at 50 percent of the number in the US and the EU-27, and as much as 80 percent of the number in Japan. (Figure 6). Steady growth in scientific human resources in the 2000s let China overtake Japan and approach the US and the EU-27 in terms of number of researchers (full-time equivalent). Since the mid 1990s, enrollment in postgraduate programs in science and engineering in Chinese universities has grown rapidly, at an average annual rate of 50 percent (Figure 7). In 2006 and 2007, China added 200 thousand new students each year to its science and engineering postgraduate programs and around 150 thousand graduates to its labor market. Total enrollment increased steadily, by a factor of six, from nearly 100 thousand in 1995 to almost 600 thousand in 2007. We argue that, with strengthened R&D funding, China has significantly increased the scale of its training programs as it produces a growing number of scientists and engineers for nanotechnology R&D. Such increased funding for research in the field also creates more employment opportunities for graduates of science and engineering programs and makes it easier to retain them within the academic community. China has therefore met the fifth target set in the Strategy with regard to fostering human resource development and training high caliber research personnel.

(Insert Figure 6 here)

(Insert Figure 7 here)

4.3 Scientific Research

As seen in Section 1, China has made impressive progress in basic science research, rapidly catching up with Japan, Germany, France, and the UK in terms of the number of Web of Science publications it produces. Importantly, China's rise in the field of nanotechnology should not be viewed as an isolated development. China indeed improved its scientific research more broadly over the same period. The annual Chinese scientific output measured by number of Web of Science articles increased fivefold, from 20,000 to 100,000 between 1998 and 2007 (Figure 8). If the number of Chinese nanotechnology publications is plotted together with the number of total scientific publications, the two lines follow the same trend.

(Insert Figure 8 here)

The reform and transformation of the Chinese science and technology system also contributed to a boom in Chinese nanotechnology publications. China inherited a science and technology system from the era of the planned economy. It consisted of a large number of institutions that were administered under the Chinese Academy of Sciences and affiliated with ministries. Since

1985, the system has undergone continuous transformation. Enhancing efficiency and increasing scientific output are among the goals of the series of reforms [27]. To evaluate the scientific output of scientists and research units, Chinese universities and research institutions, starting in the mid 1990s, began using the number of articles in the Science Citation Index (one of the three databases included in the Web of Science) to measure research performance. In many prestigious Chinese universities even graduate students were required to publish in journals indexed by the Web of Science in order to obtain their degrees. Chinese universities competed with each other in funding applications according to the number of Web of Science publications. The adoption of this evaluation criterion by the academic community resulted in explosive growth in Web of Science publications produced by Chinese scientists.[3]

It is, of course, important to determine whether the quality of the publications produced by Chinese universities and research institutions increased in tandem with the number of publications. Quantity alone does not indicate the impact of Chinese research. We develop a bibliometric indicator based on citations to measure the quality of nanotechnology publications produced by the most prolific countries and institutions worldwide. It is known that articles or journals that publish basic science research outcomes should be cited, on average, more often than those focusing on applied science are. Similarly, institutions that are committed to basic research should receive more citations of their publications than those working in applied science fields. To correct this bias of measurement regarding citations, we use the aggregate impact factors of subject categories in the *Journal Citation Reports* of the Web of Science to discount the advantage associated with basic science research.[4]

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[3] This prevalent evaluation criterion was criticized however by many observers, who argued that it made Chinese scientists overly focused on publishing in low-impact (easy) journals indexed by Science Citation Index in order to obtain a larger number of publications, instead of improving the quality of their research to publish in high-impact (difficult) journals [28].

[4] *Journal Citation Reports* science edition indexed 6,426 journals in its 2007 issues, which are classified into 172 subject categories. *Journal Citation Reports* publishes an aggregate impact factor for each journal and subject category from 2003 onwards. An aggregate impact factor for a subject category of 1.0 indicates that, on average, articles in that subject category published one or two years earlier have been cited just once. As seen in *Journal Citation Reports*, articles published one or two years earlier in journals that fall into the subject category of materials science & ceramics were, on average, cited 0.9 times. Articles in the subject category of physics, atomic, molecular & chemical were cited 2.3 times. Let’s assume that publications from Institution A, which largely fall into the category of material science and ceramics, were cited 1.8 times. This means that the quality of publications of Institution A is well above the world average level, which is 0.9. If we assume, however, that publications from Institution B, which are mainly in the field of physics, atomic, molecular & chemical, were cited also 1.8 times, then the quality of Institution B publications is inferior to the world average level, which is 2.3. It thus would be

Acknowledging differences in citation patterns of publications in various subject categories, we multiply the share of the total publications of an institution in each of the 172 subject categories of *Journal Citation Reports* by the aggregate impact factor of each subject category and sum the products together. The sum of the products can be understood as the expected cited times of publications from this institution given its publication portfolio, assuming the quality of its publications reaches the world average level.[5] After obtaining expected cited times of publications for each of the most prolific institutions, we subsequently divide the actual cited times of their publications by the expected cited times to get a citation score for each of these institutions. By the same token, the citation scores for the world's most prolific countries are calculated as well.

Table 3 shows that China was ranked 35th in the world by citation score in 1998. Its ranking had improved to 23rd by 2002 but dropped to 27th in 2006, well behind the most advanced countries in the world. Most Chinese universities score much higher when ranked by number of nanotechnology publications than by citation scores (Table 4). It is well known, however, that citation is only one proxy among others to indicate the quality of a publication. In addition, citation is affected by multiple factors other than quality of publication, such as network of scholars and the openness of a national innovation system [29, 30]. A scholar who is more visible and active in the international academic community is more likely to be cited by peers in other countries. This is why we argue that China can benefit from international collaboration if it wishes to enhance its nanotechnology research profile and accordingly achieve greater global impact. From 1998 to 2007, about 17 percent of Chinese nanotechnology papers involved international collaboration. Figure 9 shows that the top 20 countries with which Chinese scholars collaborated in nanotechnology include the US, Japan, Germany, Singapore, and the UK, among others. Collaborative articles with scientists from the US accounted for just over 5 percent of total Chinese nanotechnology publications in the period of 1998–2007. The percentage of cited articles co-authored with scientists from these 20 countries is invariably higher than the percentage of cited Chinese non-collaborative articles, which clearly indicates that Chinese

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misleading to directly compare the average cited times of nanotechnology publications from different institutions or countries without considering differences in subject categories of those publications.

[5] For example, if an institution has one-third of its publications in the category of materials science & ceramics, and the remaining two-thirds in physics, atomic, molecular & chemical, the expected cited times would equal 0.9*0.33+2.3*0.67=1.84.

scientists have benefited from the “international collaboration dividend,” as coined by Tyfield et al [30].

(Insert Table 3 here)
(Insert Table 4 here)
(Insert Figure 9 here)

To summarize, China has strengthened its basic nanotechnology science research (the first target set in the Strategy), as measured by number of scientific publications. However, the citation rates of Chinese publication still lag behind those of the most advanced countries. Whether or not we can rigorously interpret citation as a proxy for quality of publications, China has benefited from international collaboration as collaborative works with foreign scholars have received more citations than works authored only by Chinese scholars, and thus have had greater impact. We argue that China should continuously to focus on and make efforts to promote international collaboration, which will create a win-win situation not only for Chinese scientists but also for their international peers.

4.4 Commercialization and application of the technologies

The intensive public investment in nanotechnology R&D in China we have observed over the past decade has paid off to a certain degree, as China has produced the second highest number of scientific publications in the world after 2003, trailing only the US. However, scientific publication itself is not the ultimate goal of technology development. Ideally, China’s lead in basic science research would be transformed into the competitiveness of traditional industries that are upgraded by nanotechnology or by the emergence of new industries and employment opportunities that can bring economic growth. We argue that China has not yet performed extraordinarily in this regard.

First, industry R&D has remained weak. Corporate funding in China was only 40 percent of government funding during the period of 2005–2007 (Figure 3). In contrast, industry in general accounted for 72.3 percent of total Chinese R&D expenditure in 2007 [31]. Differing from what has occurred in China, corporate funding by American and Japanese enterprises far surpassed government funding, arguably because firms from these two countries were equipped with advanced technological capabilities that allow them to appropriate the return on R&D investment. Bai [21] estimated that only about 300 firms in China engaged in business activities related to nanotechnology in 2005. The majority of indigenous Chinese firms have not established a high level of international competitiveness based on technological advancement, innovation, or R&D. It has been easier for them to purchase advanced production lines or blueprints from domestic or foreign suppliers and leverage their low-cost manufacturing capability to compete domestically or internationally. Seeking to transfer cutting-edge technologies from universities and research institutions is costly and risky. There thus are not enough incentives from the demand side for Chinese firms to engage in nanotechnology R&D. That's why, percentage-wise, Chinese nanotechnology patent applications accounted for only a tiny share, 0.5 percent, 0.5 percent, and 0.2 percent of the world's accumulated applications in the US Patent Office (USPTO), the European Patent Office (EPO), and the Japanese Patent Office (JPO), respectively (Table 5).

(Insert Table 5 here)

In addition, among these patent applications, 50 percent were filed by public organizations including universities, research institutes, and the Chinese Academy of Sciences. Only 42 percent were applied for by industry representatives (Figure 10), whereas in other industrialized countries industry is the main performer of industrial development and leading patent applicant. Although China gained on the leading patenting countries with a high growth rate in patent applications (Figure 2), a substantial proportion of these patent applications were filed by universities and research institutions, given the weak patenting performance of indigenous Chinese companies. A study conducted by Parker et al. [32], which examines patent applications submitted to the Chinese Patent Office (State Intellectual Property Office) from 1991 to 2006, resulted in a similar finding that 63 percent of nanotechnology patents originating in China originated either with Chinese universities or with the Chinese Academy of Sciences. By contrast, an overwhelming majority of US applications to the Chinese Patent Office were from the private sector. Through interviews with nanotechnology scientists and companies, Shapira and Wang [33] offered an explanation of these findings. Scholars in the Chinese Academy of Science and from universities were incentivized to apply for patents because patent applications as well as publications were important elements for career development and promotion, and also for meeting the deliverable targets of their research projects funded by the government. In contrast, most indigenous Chinese companies lacked technological capabilities on the basis of which to fully assess the prototype technology developed in public research institutions and universities. Such organizations were established for the purpose of profiting from their core technologies and have no long-term research agenda. In addition to seeking modest technological advice and using equipment and facilities, these companies did not interact to a significant extent with universities or research institutions.

(Insert Figure 10 here)

A close look of the geographical distribution of Chinese academic nanotechnology research centers and patent application and commercialization hotspots convinces us that the academic research supporting technology and industrial development and production is performed in various locations with only loose links between them. As seen in Table 6, Beijing, the capital city in the north, hosted 22.2 percent of the departments or institutions that published more than 50 publications and filed 37.4 percent of the country's patent applications. However, Beijing hosted only 6.4 percent of the listed companies that engage in business activities related to nanotechnology.[6] Controlling for the share of general listed companies from Beijing in China's total listed companies (7.7 percent), we confirm that 6.4 percent is actually smaller than what would be expected if nanotechnology-related business activities were distributed equally across the country. Beijing is a center of academic research and patenting activities, but not a hotspot of industrial development and production.

(Insert Table 6 here)

Guangdong in Southern China is, by contrast, home to merely 1.9 percent of the departments or institutions that have published more than 50 nanotechnology articles or applied for 8.3 percent

[6] The analysis of nanotechnology-related business activities is performed only on listed companies. There is no statistical information available for nanotechnology start-ups or small and medium enterprises in China, although they are considered to be important in commercializing new technologies as well.

of patents, but it hosted 12.1 percent of the listed companies engaging in nanotechnology-related business. Guangdong is definitely not an academic research center, but it is an important location for industrial applications. Similar to Guangdong, Zhejiang accounted for a small share in basic research and patent applications, but concentrated a significant share in industrial activities. Readers are advised that Beijing, Guangdong, Zhejiang, Jiangsu and Shanghai plus Tianjin are the six most highly developed provinces in China in terms of GDP per capita and all are known for having sound infrastructure, an open business environment, abundant financial resources, and a concentration of human resources. There is no other reason to explain the conspicuous differences in their respective performances in nanotechnology R&D and related business activities other than that basic research, technology development, and industrial production of nanotechnology in China are carried out separately. An increasing proportion of public funding was poured into universities and research institutions affiliated with the Chinese Academy of Sciences, which are largely concentrated in Beijing and Shanghai (Beijing, Shanghai and Hong Kong alone produced almost half of all Chinese nanotechnology publications). Such public R&D investment has resulted in a boom in scientific publications and expansion of the research system in some locations. However, the commercialization of technology has been weak, and industrial development and production have remained detached from the scientific research system.

As discussed in Section 4.2, a number of new institutes established to promote commercialization were set up within the Science Park or near industrial zones in Shanghai and other cities such as Tianjin (the China National Academy of Nanotechnology and Engineering and Nanotechnology Industrialization Base of China) and Suzhou (the Suzhou Institute of Nano-tech and Nano-bionics, the Chinese Academy of Sciences, and the Suzhou BioBay in Sino-Singapore Industrial Park). To meet the third target of the Strategy with regard to commercialization, China needs to continue its effort along this channel to further strengthen industry-academy collaboration.

To summarize, China has made tremendous efforts over the past decade to develop and promote nanotechnology. An evaluation of the Chinese performance according to targets set in the national strategy announced in 2001 points out that China has performed well in areas such as strengthening basic research, constructing nanotechnology-related databases, and developing national standards; in establishing national key laboratories and research centers in the field with substantial government investment; and in fostering human resource development and training high caliber research personnel. However, China has encountered enormous difficulty in commercializing the technology and upgrading traditional industries through nanotechnology, due to the limited technological capabilities of indigenous companies and a lack of incentives to induce them to actively engage in industrial development and commercialization.

5 Conclusion: The China Model

In an early study, Perez and Soete [15] argued that minimal fixed investment, skills and experience, location advantages, and scientific and technological knowledge are the four barriers facing latecomers when entering an emerging field or industry. In the past decade since China launched its national strategy to promote nanotechnology development, the country has devoted an increasing amount of R&D investment to the field, produced a soaring number of scientific publications, established several new specialized institutions, and expanded its postgraduate program in science and engineering to train nanotechnology scientists and engineers. China’s improvement is real and substantial, not a scientometric mirage. All these achievements indicate that China has been accumulating sufficient science and technological knowledge to overcome the entry barriers. Given that nanotechnology is still in an initial stage of commercialization, requirements in terms of fixed investment, skills and experience, and location advantages should not be extremely high. The hope that China can pass through a window of opportunity to catch up and become a leading nation in the field has never been higher.

It may take quite a long time for public investment on the part of the Chinese government to pay off, given the uncertainty of nanotechnology. However, the absence of funding will definitely lead to the certainty of obsolescence. As the US, Europe, Japan, and numerous national and regional governments launched their respective nanotechnology development strategies in the late 1990s and the beginning of the 2000s, it would be only logical for China to jump on the bandwagon. In this sense, China’s large and resolute public investment in nanotechnology R&D is more of a sure bet because only with it can China enjoy a first mover’s advantage in nurturing human resources, developing R&D capacity, and promoting learning capablities, all of which will ultimately result in a higher probability that indigenous industry will emerge and compete effectively in the global arena.

An evaluation of the Chinese performance according to targets set in the national strategy a decade ago points out, however, that China has still lagged behind most of the advanced countries in terms of the impact (citations) of its scientific research. China has not yet performed satisfactorily in the areas of commercialization and application of the technology. Percentage-wise, China has accounted for only a tiny share in the accumulated nanotechnology patent applications in US, EU, and Japanese patent offices. Evidence shows that basic research, technology development, and industrial production of nanotechnology in China are carried out in separate systems and locations and are detached from each other. Due to limited the technological capabilities of indigenous companies and a lack of incentives for them to actively engage in R&D, the major challenges for latecomer countries such as China that seek to further catch up with the advanced leaders remain in the area of commercialization. Whether China can successfully promote academy-industry collaboration, or leverage venture capital or other means to facilitate technology transfer from labs to firms will ultimately determine China's catching-up performance in the nanotechnology field.

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Table 1: The 30 Most Prolific Departments or Institutions of China in Nanotechnology: 1998–2007

Rank	Number of Web of Science articles	University or Institution	Department	City and Province
1	2360	Chinese Academy of Sciences	Institute of Chemistry	Beijing
2	1713	Chinese Academy of Sciences	Institute of Physics	Beijing
3	1668	Chinese Academy of Sciences	Graduate School	Beijing
4	1485	Chinese Academy of Sciences	Changchun Institute of Applied Chemistry	Changchun, Jilin Province
5	1472	Nanjing University	Department of Physics	Nanjing, Jiangsu Province
6	1288	Chinese Academy of Sciences	Shanghai Institute of Ceramics	Shanghai
7	1178	University of Science and Technology of China	Department of Chemistry	Hefei, Anhui Province
8	1139	Jilin University	Department of Chemistry	Changchun, Jilin Province
9	1075	Peking University	College of Chemistry and Molecular Engineering	Beijing
10	889	Tsinghua University	Department of Material Science and Engineering	Beijing
11	850	Tsinghua University	Department of Chemistry	Beijing
12	805	University of Science and Technology of China	Structure Research Laboratory	Hefei, Anhui Province
13	774	City University of Hong Kong	Department of Physics and Material Science	Hong Kong
14	722	Fudan University	Department of Chemistry	Shanghai
15	663	Chinese Academy of Sciences	Lanzhou Institute of Chemical Physics	Lanzhou, Gansu Province
16	583	Chinese Academy of Sciences	Institute of Solid State Physics	Hefei, Anhui Province
17	527	Wuhan University	Department of Chemistry	Wuhan, Hubei Province
18	489	Nankai University	Department of Chemistry	Tianjin
19	473	Peking University	Department of Physics	Beijing
20	473	Tsinghua University	Department of Physics	Beijing
21	465	Zhejiang University	Department of Material Science and Engineering	Hangzhou, Zhejiang Province
22	464	Zhejiang University	Department of Chemistry	Hangzhou, Zhejiang Province
23	404	Zhejiang University	State Key Laboratory of Silicon Material	Hangzhou, Zhejiang Province
24	397	Shandong University	State Key Laboratory of Crystal Material	Jinan, Shandong Province
25	365	China Center of Advanced Science and Technology World Laboratory		Beijing
26	341	University of Hong Kong	Department of Physics	Hong Kong
27	337	Chinese Academy of Sciences	Shanghai Institute of Technical Physics	Shanghai
28	327	Wuhan University	Department of Physics	Wuhan, Hubei Province
29	323	Zhejiang University	Department of Physics	Hangzhou, Zhejiang Province
30	322	University of Hong Kong	Department of Chemistry	Hong Kong

Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors’ own calculation.

Table 2: The Location of Departments or Institutes Producing 50 Web of Science Nanotechnology Publications or More, 1998–2007

City Name	Abbreviation	Number of Departments and Institutes	Percent
Beijing	BJ	58	22.2%
Shanghai	SH	37	14.2%
Hong Kong	HK	26	10.0%
Hefei	HF	18	6.9%
Changchun	CC	14	5.4%
Nanjing	NJ	14	5.4%
Wuhan	WH	12	4.6%
Jinan	JN	9	3.4%
Shenyang	SY	8	3.1%
Changsha	CS	7	2.7%
Hangzhou	HZ	6	2.3%
Lanzhou	LZ	6	2.3%
Chengdu	CD	5	1.9%
Dalian	DL	5	1.9%
Guangzhou	GZ	5	1.9%
Tianjin	TJ	5	1.9%
Xiamen	XM	4	1.5%
Harbin	HB	3	1.1%
Xian	XA	3	1.1%
Fuzhou	FZ	3	1.1%
Kaifeng	KF	2	0.8%
Suzhou	SZ	2	0.8%
Baoding	BD	1	0.4%
Chongqing	CQ	1	0.4%
Liaocheng	LC	1	0.4%
Qingdao	QD	1	0.4%
Taiyuan	TY	1	0.4%
Urumqi	UQ	1	0.4%
Wuhu	WU	1	0.4%
Xiangtan	XT	1	0.4%
Zhengzhou	ZZ	1	0.4%
Total		261	100.0%

Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors' own calculation.

Table 3: Ranking of China by Citation Scores among the World's Most Prolific Countries (Regions) and European Union Member States (1998, 2002, and 2006)

Rank	2006		2002		1998	
	Country (Region)	Citation Score	Country (Region)	Citation Score	Country (Region)	Citation Score
1	Netherlands	2.589	USA	9.747	Switzerland	14.243
2	Switzerland	2.369	Switzerland	8.485	USA	14.036
3	USA	2.265	Belgium	8.309	Netherlands	13.862
4	Denmark	2.060	Netherlands	8.028	Denmark	12.180
5	United Kingdom	2.015	Israel	8.004	Israel	11.571
6	Singapore	1.982	Denmark	7.835	Ireland	11.421
7	Germany	1.947	Austria	7.779	Sweden	11.230
8	Canada	1.912	United Kingdom	7.715	Finland	11.079
9	Israel	1.861	Ireland	7.684	United Kingdom	11.073
10	Spain	1.861	Finland	7.634	Canada	10.448
11	Australia	1.855	Singapore	7.535	Singapore	10.241
12	Austria	1.824	Germany	7.520	Germany	10.136
13	Sweden	1.772	France	6.916	France	9.366
14	France	1.720	Canada	6.856	Belgium	8.912
15	Ireland	1.696	South Korea	6.846	Austria	8.880
16	Belgium	1.688	Sweden	6.782	Australia	8.439
17	Finland	1.671	Australia	6.695	Estonia	8.302
18	Portugal	1.574	Italy	6.621	Spain	8.223
19	Italy	1.574	Spain	6.395	Japan	7.913
20	Japan	1.532	Taiwan	6.199	Italy	7.911
21	Czech Republic	1.476	Portugal	6.026	Hungary	7.821
22	Greece	1.442	Japan	5.902	Portugal	7.571
23	South Korea	1.428	**Peoples R China**	**5.418**	Greece	7.375
24	Estonia	1.396	Latvia	5.368	Slovenia	6.915
25	Slovenia	1.361	Greece	5.283	Latvia	6.700
26	Taiwan	1.359	Slovenia	5.201	Lithuania	6.659
27	**Peoples R China**	**1.327**	Czech Republic	5.189	Brazil	6.547
28	Hungary	1.224	Hungary	5.081	Czech Republic	6.242
29	Bulgaria	1.182	Turkey	4.747	South Korea	6.084
30	Latvia	1.176	India	4.669	India	5.930
31	India	1.149	Mexico	4.495	Taiwan	5.876
32	Lithuania	1.143	Bulgaria	4.485	Romania	5.758
33	Poland	1.136	Romania	4.442	Turkey	5.430
34	Brazil	1.076	Brazil	4.254	Mexico	5.367
35	Slovakia	1.041	Poland	4.010	**Peoples R China**	**5.285**
36	Turkey	1.011	Lithuania	3.746	Poland	5.206
37	Russia	0.980	Slovakia	3.741	Slovakia	5.049
38	Mexico	0.927	Russia	3.335	Bulgaria	4.962
39	Ukraine	0.851	Estonia	3.263	Russia	4.628
40	Romania	0.827	Ukraine	3.177	Ukraine	3.738

Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors' own calculation.
Note: 1. The citation scores of 1998 are greater than those of 2002 and 2006 because by April, 2008, when the analysis was performed, articles published in 1998 had been cited more times than those published more recently, e.g., in 2002 or 2006.

Table 4: Ranking of Chinese Institutions that are among the World's 150 Most Prolific Institutions by Citation Scores

Institution	Country	Citation Score	Rank by Citation Score	Rank by Number of Publications in 2006
Hong Kong Univ Sci & Technol	Hong Kong, China	2.391	33	109
Peking Univ	China	1.919	77	29
Hunan Univ	China	1.729	94	112
Nankai Univ	China	1.681	99	66
Nanjing Univ	China	1.674	101	21
Tsing Hua Univ	China	1.664	103	5
City Univ Hong Kong	Hong Kong, China	1.641	106	125
Univ Sci & Technol China	China	1.575	115	17
Chinese Acad Sci	China	1.575	116	1
Fudan Univ	China	1.547	119	25
Dalian Univ Technol	China	1.449	127	119
Shanghai Jiao Tong Univ	China	1.417	130	28
Wuhan Univ	China	1.278	132	67
Jilin Univ	China	1.259	134	23
Zhejiang Univ	China	1.255	135	10
Tianjin Univ	China	1.169	139	71
Shandong Univ	China	1.112	142	68
Harbin Inst Technol	China	0.986	146	81
Huazhong Univ Sci & Technol	China	0.966	147	97
Sichuan Univ	China	0.793	149	91

Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors' own calculation.

Table 5: Share of Accumulated Nanotechnology Patent Applications in the US Patent Office, European Patent Office and Japanese Patent Office: 1928–2009 (Percentage)

USPTO		EPO		JPO	
US	50.3	US	30.5	Japan	95.4
Japan	20.3	Japan	20.6	US	2.0
Germany	3.6	Germany	15.9	Germany	0.4
South Korea	3.3	France	5.9	France	0.3
France	1.9	UK	4.8	South Korea	0.2
UK	1.8	Netherlands	3.1	UK	0.2
Netherlands	1.7	Switzerland	2.7	Switzerland	0.2
Taiwan	1.4	South Korea	2.4	China	0.2
Canada	1.1	Italy	1.7	Other Countries	1.0
Switzerland	0.9	Belgium	1.4		
China	0.5	China	0.5		
Other countries	13.1	Other Countries	10.5		

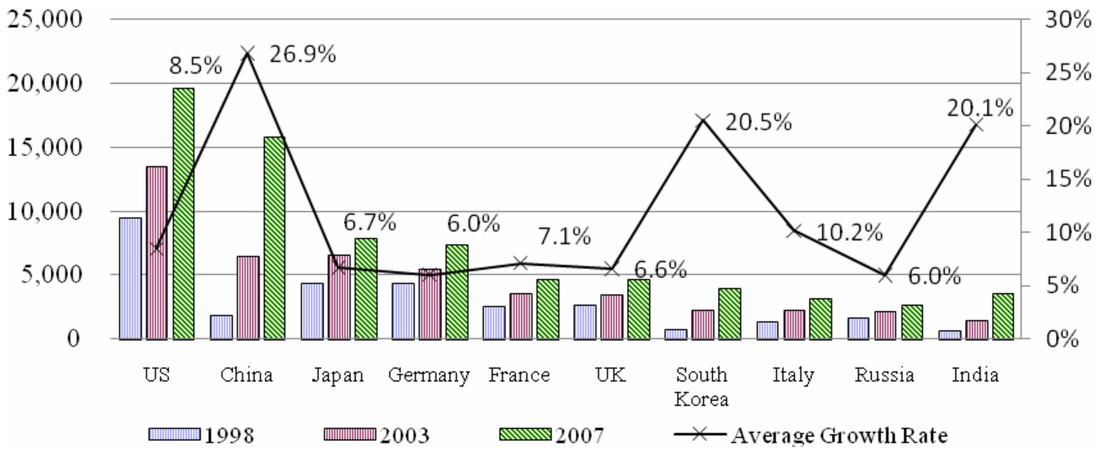
Data source: PATSTAT database (September 2009 version). Authors' own calculation.

Table 6: Geographical Mismatch of China's Nanotechnology Academic Research Centers, Patent Applications, and Commercialization Hotspots

Provinces	Number of the departments or institutions with more than 50 nanotechnology publications (Percentage in national total)	Number of nanotechnology patent applications in PASTAT databse (Percentage in national total)	Number of listed nanotechnology companies (Percentage in national total)	Number of general listed companies (Percentage in national total)
Beijing	58 (**22.2%**)	279 (**37.4%**)	10 (**6.4%**)	135 (**7.7%**)
Guangdong	5 (**1.9%**)	60 (**8.3%**)	19 (**12.1%**)	240 (**13.7%**)
Jiangsu	16 (6.1%)	41 (5.5%)	15 (9.6%)	129 (7.4%)
Shanghai	37 (14.2%)	81 (10.8%)	19 (12.1%)	159 (9.1%)
Zhejiang	6 (**2.3%**)	6 (**0.8%**)	15 (**9.6%**)	143 (**8.2%**)
National total	261 (100.0%)	743 (100.0%)	157 (100.0%)	1751 (100.0%)

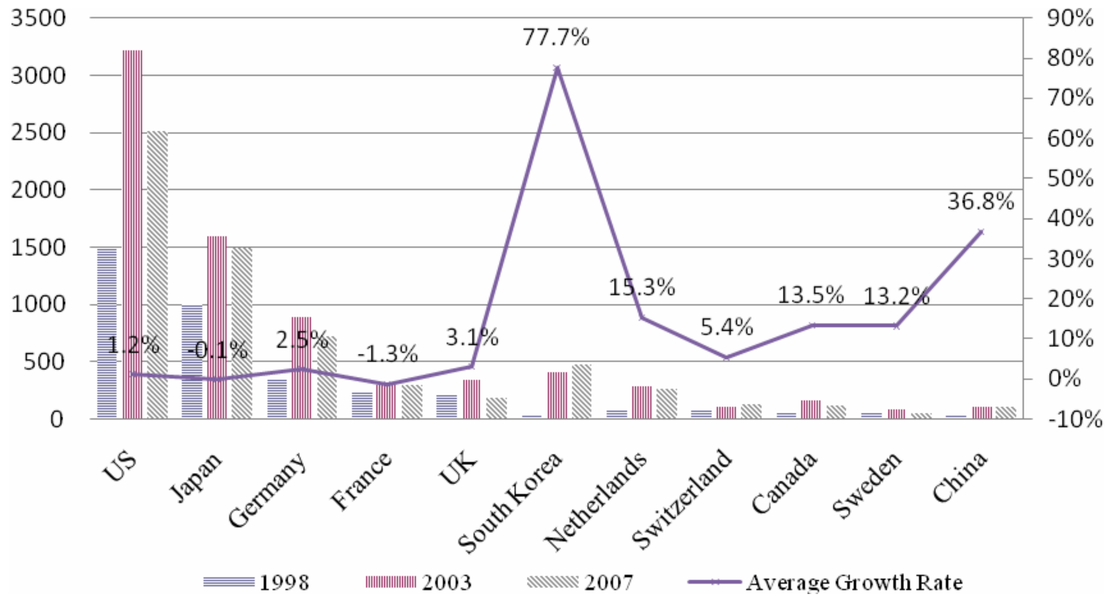
Source: Authors' own calculation.
Note:
1. The listed nanotechnology companies are the listed firms that have declared that they engage in business activities related to the technology in their annual reports. Annual reports of the Chinese listed companies are from the China Infobank database.

Figure 1: The World's 10 Most Prolific Countries in the Nanotechnology Field: 1998–2007



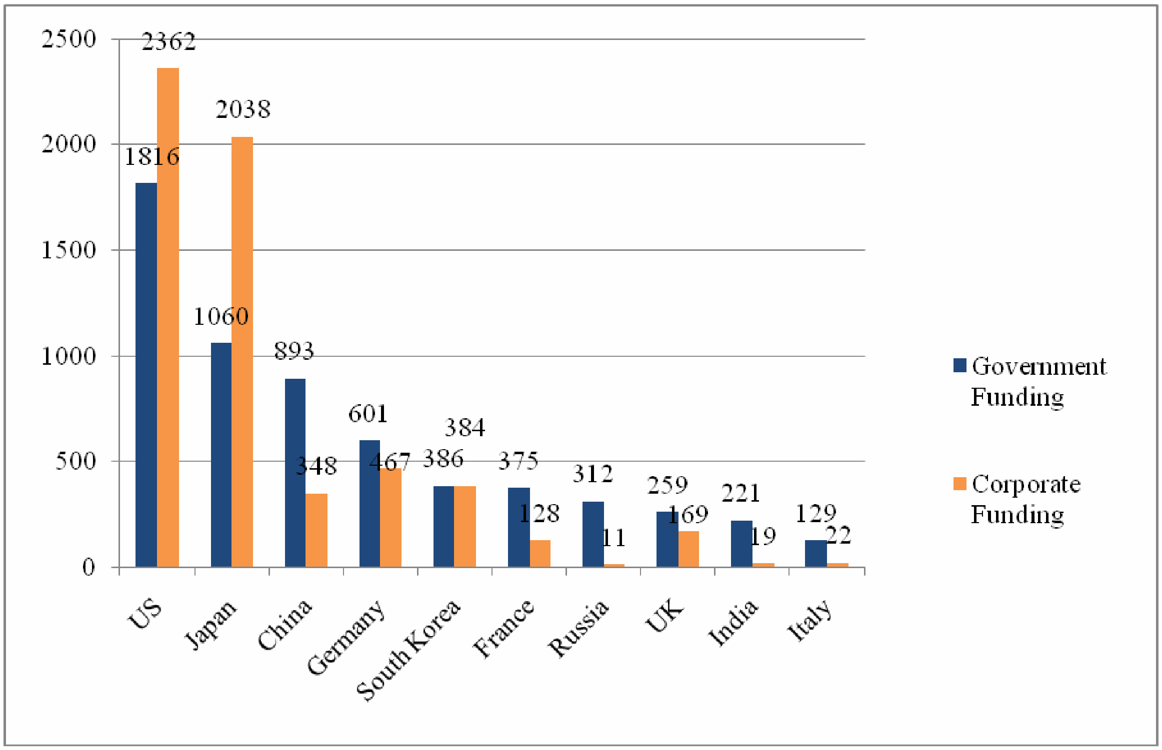
Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors' own calculation.

Figure 2: The Top 10 Countries and China (13th) in terms of Nanotechnology Patent Application: 1998–2007



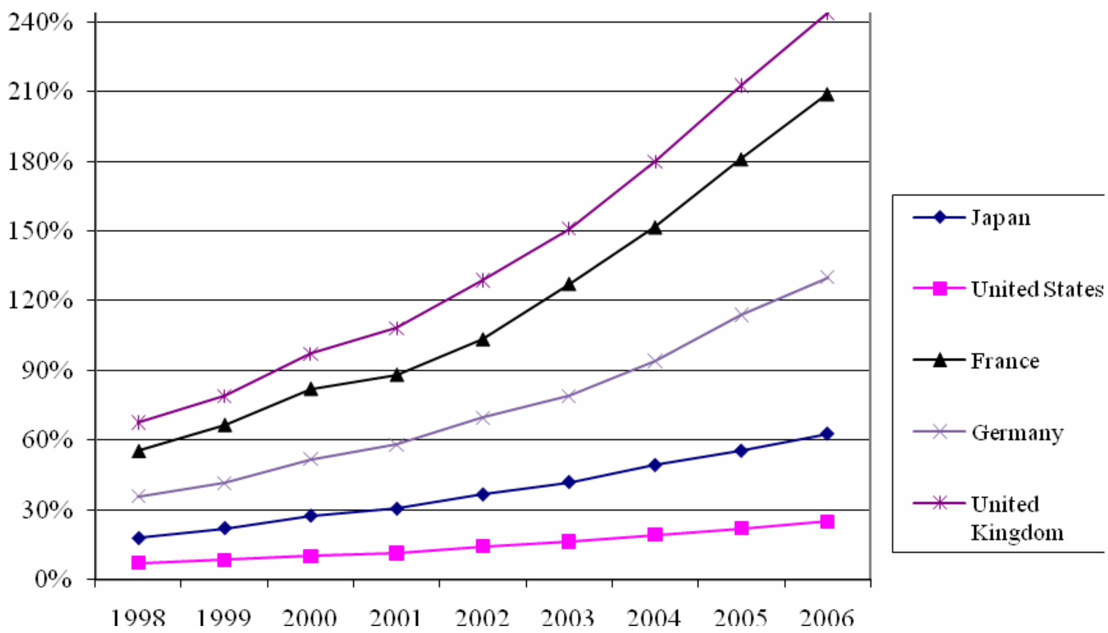
Data source: PATSTAT database (September 2009 version). Authors' own calculation.

Figure 3: Estimated Government and Corporate Nanotechnology Funding (PPP US$ Million), 2005–2007



Source: Lux Research (2008).

Figure 4: China's Gross Expenditure on R&D (million current PPP $) as a Percentage of the R&D Expenditure of France, Germany, Japan, the UK and the US (1998–2006)

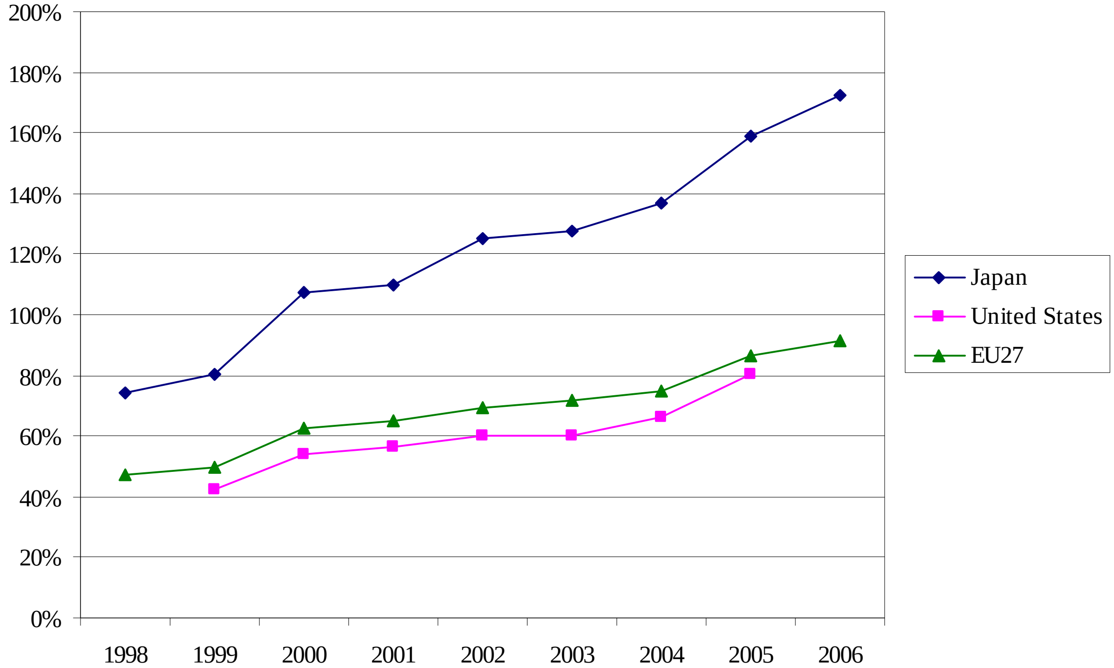


Source: OECD Science and Technology Statistics.

Figure 5: The Location of the Departments or Institutes Producing 50 Web of Science Nanotechnology Publications or More, 1998–2007

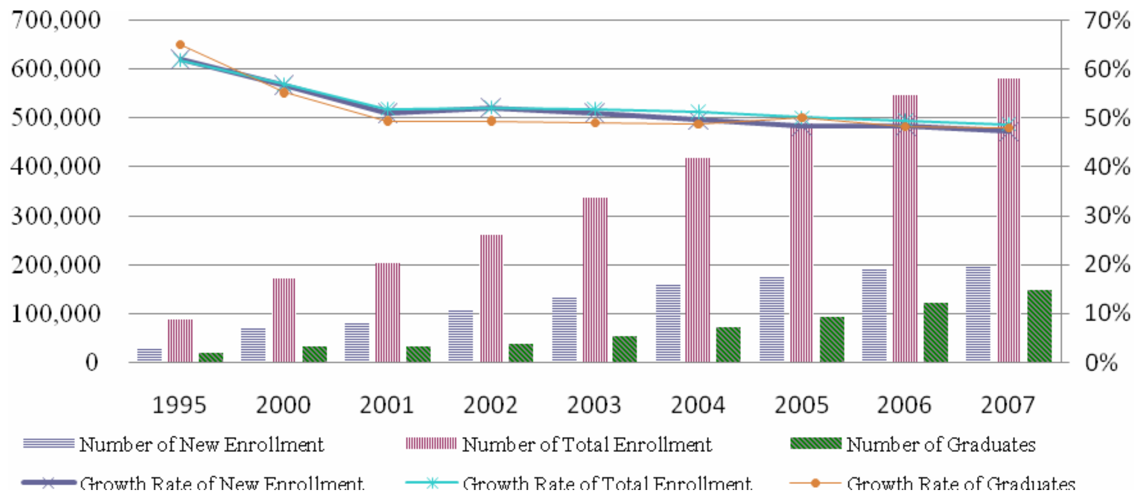
Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors’ own calculation.
Note: 1. Abbreviation of city names are seen in Table 2.

Figure 6: China’s Total Researchers (Full-Time Equivalent) as a Percentage of the Total Researchers of the US, EU-27 and Japan (1998–2006)



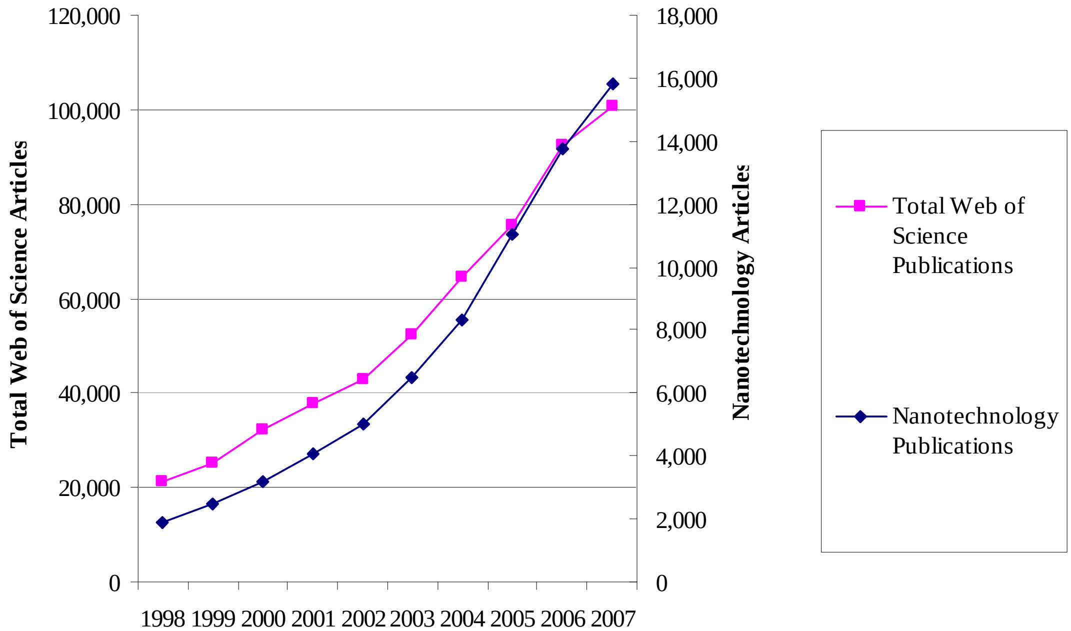
Source: OECD Science and Technology Statistics.

Figure 7: Number and Growth of Enrollment and Graduates of Postgraduate Programs in the Field of Science and Engineering in China: 1995–2007



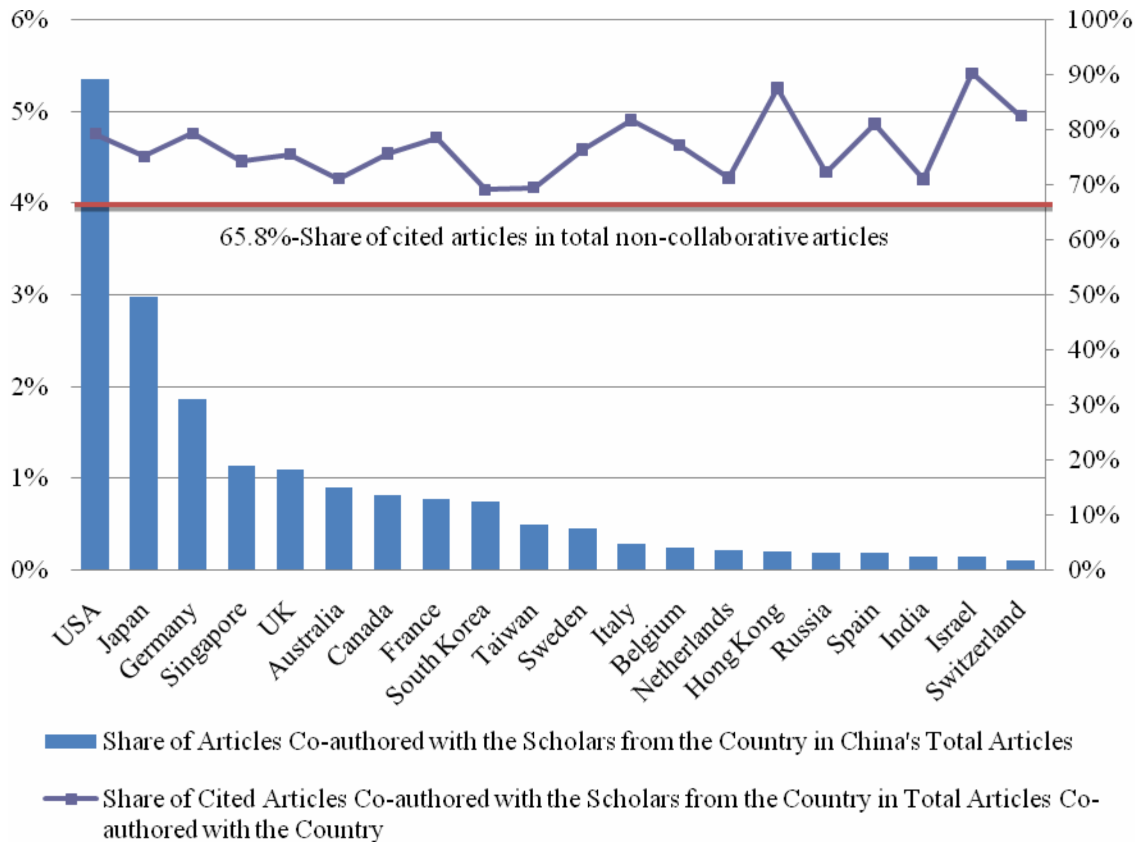
Source: various issues of *China Statistical Yearbook*.

Figure 8: China's Total Scientific Publications and Nanotechnology Publications Indexed by the Web of Science



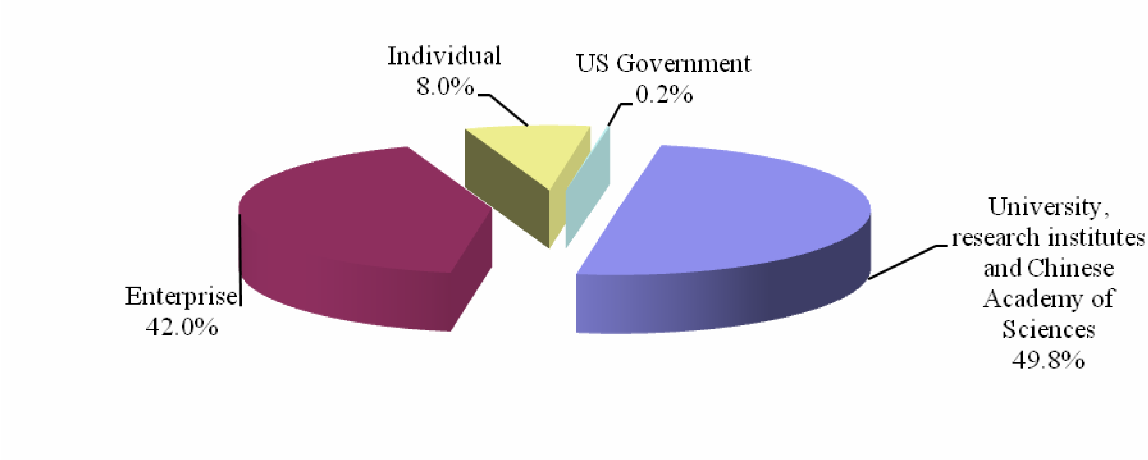
Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors' own calculation.

Figure 9: Comparison of the Shares of Cited Articles among the Chinese Collaborative Articles and Non-Collaborative Articles: 1998–2007



Data source: MERIT Database of Worldwide Nanotechnology Scientific Publications. Authors' own calculation.

Figure 10: Breakdown of the Chinese Nanotechnology Patent Applications by Types of Assignees



Data source: PATSTAT database (September 2009 version). Authors' own calculation.

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